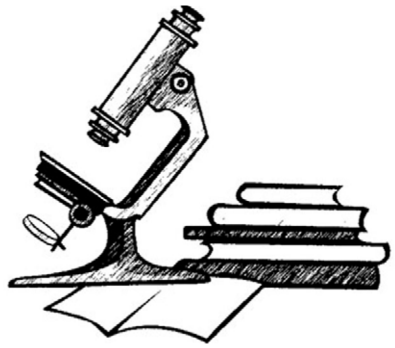


Research, reviews & patents

GaN on silicon

GaN-based devices continue to demonstrate high performance not only for blue and ultraviolet LEDs but also for RF high-power and high-temperature components. However, commercial III-nitride LEDs are usually grown by MOCVD on sapphire or SiC substrates. The industry is always looking to improve economics, hence the interest in other dissimilar substrates and silicon in particular. Silicon has obvious attractions as a substrate for III-nitride devices, i.e. cost effectiveness and the possibility of integration with the silicon electronics.

But these advantages will not be reached without considerable technical development. It is still difficult to get crack-free and device-quality GaN-on-Si thanks to the large mismatches in lattice and thermal expansion coefficient between the epilayer and the substrate. Moreover, GaN is difficult to nucleate on silicon because of surface passivation by nitrogen from the source gas. For such reasons, the GaN epilayer quality and device performance have not been comparable to those obtained on sapphire. For example, Armin Dadgar and fellow workers at Germany's Otto-von Guericke Universität Magdeburg have found a way to grow GaN on Si. They were able to fabricate high-brightness InGaN/GaN LED on Si(111) substrates via low-temperature AlN and Si_xN_y interlayers. Results include packaged LED structures with an output power of 0.42 mW at 498 nm and 20 mA, which is the best light power output ever reported for GaN-based LED on Si substrate.

Despite this promising achievement, the LED has a higher-than-desired operating voltage, plus a large series resistance. Now, a group of workers at the Education Ministry Engineering Research Center for Luminescence Materials and Devices at Nanchang University, in China have reported the growth of a high-quality InGaN multi-quantum well (MQW) LED structure on Si(111) substrates that also uses intermediate epilayers (see Figure 1). In this case, they used a using Ga-rich GaN buffer grown at high temperature and an

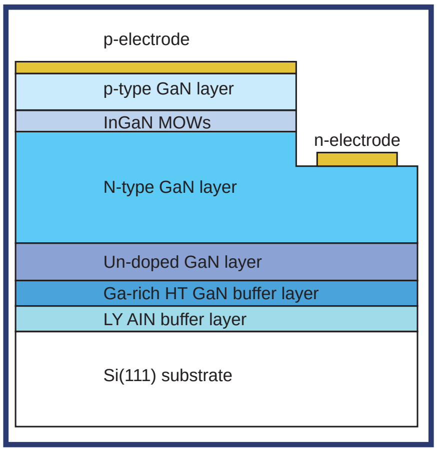


Figure 1. High-quality InGaN MQW LED structure on Si(111) substrate with intermediate epilayers of Ga-rich GaN buffer grown at high temperature and an AlN buffer layer grown at lower temperature via LP-MOCVD.

AlN buffer layer grown at a lower temperature via low-pressure MOCVD (see *Growth and characterization of InGaN blue LED structure on Si(111) by MOCVD*, Chunlan Mo, Wenqing Fang, Yong Pu, Hechu Liu and Fengyi Jiang, *Journal of Crystal Growth*, volume 285, issue 3 (1 December 2005), pages 312-317).

Crack-free films were obtained; the full width half maxiumums (FWHMs) of the (002) and (102) x-ray rocking curves were 343 and 520 arcsec, respectively. This shows that the LED structure is of high crystalline quality. In terms of operating parameters, the operating voltage was 3.8 V, the turn-on voltage about 2.5 V, and the series resistance was 47 Ω. The electroluminescence (EL) peaks at 460 nm, with a FWHM of about 28 nm at a current of 20 mA. In addition, the LED shows an EL intensity of 20 mcd at an injection current of 20 mA. These characteristics are comparable to those of LEDs on sapphire.

Patents

Meanwhile, on the patent front, the University of Florida Research Foundation, Inc has been awarded US Patent 6,967,355 by Olga Kryliouk *et al* for '*III-nitride on Si using epitaxial BP buffer layer*'. The device was made using a silicon (111) single crystal substrate and an epitaxial boron phosphide (BP) layer (see Figure 2). Quite a few different buffer layers have been tried for insertion between the Si substrate and the GaN layer to relieve lattice strain and thus improve GaN crystal quality. Even when these are used, typically the effect of the TEC mismatch is too large to suppress the formation of cracks. Thin AlN, GaAs, AlAs, SiC, SiO_2, Si_3N_4 and ZnO, boron monophosphide (BP) or low-temperature GaN layers are suitable. Notably, BP has a zincblende crystal structure with a lattice constant of 4.5383 Å at room temperature; the lattice

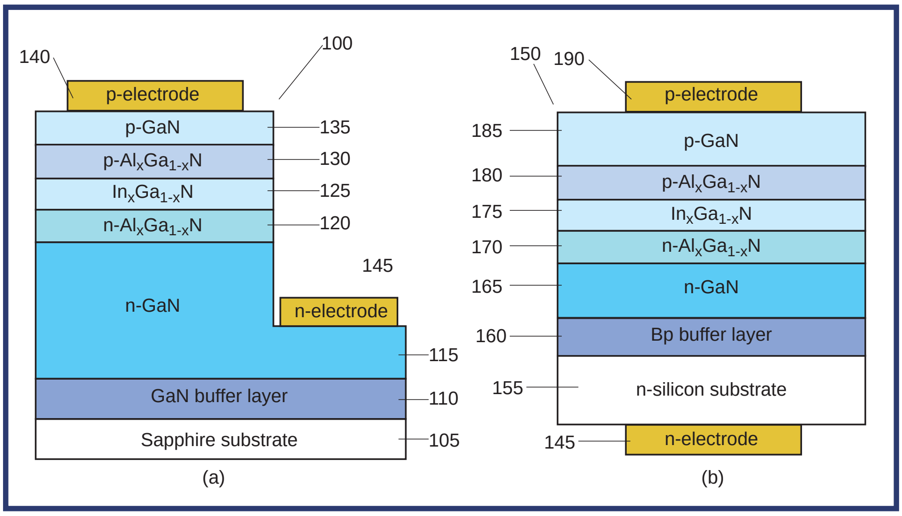


Figure 2. Growth of III-nitrides on Si using (a) a sapphire substrate and (b), instead, a Si(111) single-crystal substrate and an epitaxial boron phosphide (BP) buffer layer.

mismatch between GaN and BP is less than 0.6%, and BP is a stable material. In this work, the thickness of the BP layer is typically about 0.5-1 µm, and in the range of 0.1-1.0 µm. A group III-N layer is then grown, all with H-MOVPE at a deposition temperature in the range 560°C to 950°C. GaN was then epitaxially grown on the (111) epitaxial BP layer/Si (111) substrate. In some cases, the GaN layer was grown in an alternate reactor.

SiC by transmutation

Other interesting related patents of note come from Cree. Patent #6,964,917 for VFTsvetkov *et al* describes '*Semi-insulating silicon carbide produced by neutron transmutation doping*'. The method produces highly uniform SI characteristics in single-crystal SiC for semiconductor applications. It includes irradiation of a crystal with net p-type doping and deep levels with neutrons until the concentration of 31P equals or exceeds the original net p-type doping while remaining equal to or less than the sum of the concentration of deep levels and the original net p-type doping.

Also on substrates, SOITEC SA has been awarded a patent for a method of manufacturing a free-standing substrate made of monocrystalline semiconductor material. In US Patent 6,964,914 for B Ghyselen *et al*, a process includes a relatively thin nucleation layer of a first material, a support of a second material, and a removable bonding interface defined between facing surfaces of the nucleation layer and support. Then a relatively thicker layer of a third material is grown on the nucleation layer so as to form a second assembly and give the substrate sufficient thickness to be free-standing. The removable character of the bonding interface is preserved at epitaxial growth temperatures; the dissimilarity of the TECs of the second and third materials is a function of the growth temperature or subsequent application of external mechanical stresses, such as cooling. The stresses induced in the removable bonding interface facilitate detachment of the nucleation layer from the substrate.

The processing of substrate materials continues to present challenges in commercial production. A new patent for New Wave Research (US Patent #6,960,739) by K-C Liu *et al* describes the scribing of sapphire substrates with a solid-state UV laser.

The system performs the steps of mounting a sapphire substrate, carrying an array of integrated device die and directing UV pulses of laser energy at the surface using a solid-state laser. The pulses of laser energy have a wavelength of below about 560 nm, preferably between about 150 in 560 nm. Energy density, spot size, and pulse duration are established at levels sufficient to induce ablation of sapphire. Control of the system, such as by moving the stage with a stationary beam path for the pulses, causes the pulses to contact the sapphire substrate in a scribe pattern at a rate of motion causing overlap of successive pulses sufficient to cut scribe lines in the sapphire substrate.

Finally, in *Materials Science and Engineering: C* (volume 25, issues 5-8 (December 2005), pp 698-704, taken from *Current Trends in Nanoscience - from Materials to Applications Proceedings of the European Materials Research Society 2004 - Symposium G*) there is an interesting paper presenting details of 'onion-like' growth and inverted many-particle energies in quantum dots. Dieter Bimberg* *et al* of the Institut für Festkörperphysik, TU-Berlin, Germany show that the growth of quantum dots by MOCVD can now be controlled such that the typical mode resulting in a large inhomogeneous but continuous distribution of QD sizes and shapes switches to an 'onion-like' one. A manifold of narrow distributions differing in size by exactly one monolayer is the result.

Luminescence and excitation spectroscopy beautifully demonstrate this monolayer size-splitting by multimodal spectra whose peaks are in quantitative agreement with the numerical predictions based on eight-band k·p theory implemented using the method of finite differences.

The researchers add that, by varying the number of shells of the quantum onion, the number of bound states varies. In consequence, the magnitude of many-particle energies like exchange and correlation calculated in the frame of configuration interaction changes dramatically, resulting in a sign reversal of the biexciton binding energy. The researchers were able to observe directly the sign reversal in single-dot spectroscopy using cathodoluminescence employing a shadow mask technique.

The work was supported by the NANOMAT project of the EC's Growth Programme and by the Deutsche Forschungsgemeinschaft in the framework of SFB 296.

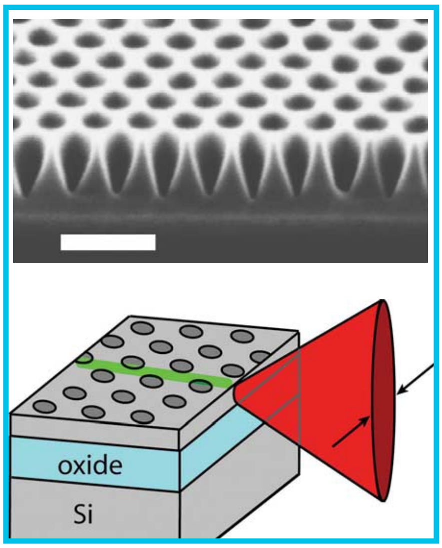
*E-mail: bimberg@sol.physik.tu-berlin.de

First directly pumped silicon laser

Researchers at Brown University in the USA, led by professor Jimmy Xu in his Laboratory of Emerging Technologies, have fabricated the first directly pumped silicon laser by changing the structure of the silicon crystal through a novel nanoscale technique (published online in *Nature Materials*).

The Brown University team created a nanoscale template (mask) of anodized aluminium about one millimeter square by drilling billions of uniformly sized and exactly ordered holes in it. Placed over a small piece of silicon then bombarded with an ion beam, the mask serves as stencil, punching out precise holes and removing atoms in the process. The silicon atoms then subtly rearrange themselves near the holes, allowing weak but true laser light emission (see the scanning electron micrograph and schematic below).

Over the course of a year, the researchers repeatedly tested lasing characteristics such as threshold behaviour, optical gain, spectral line-width narrowing, and self-collimated and focused light emission. But, to make the silicon laser commercially viable, it must be engineered to be more powerful and to operate at room temperature, says Xu (currently, it runs at 200°C below zero). A material with the electronic properties of silicon and the optical properties of a laser could find uses in both the electronics and communications industries, helping to make faster, more powerful computers or fibre-optic networks, he adds.



Scanning electron micrograph of the 'mask' used to drill holes in the silicon, and a schematic showing the laser's structure. (Courtesy of the Xu Laboratory, Brown University.)